EEDP-01-33
January 1995

Environmental Effects of Dredging Technical Notes

Trophic Transfer and Biomagnification Potential of Contaminants in Aquatic Ecosystems

Purpose

This technical note examines the potential (or lack thereof) of contaminants to biomagnify in aquatic ecosystems. This information will be useful in interpreting the environmental significance of regulatory-mandated dredged material bioaccumulation test results. Several chemical classes were examined, with emphasis placed on contaminants that are of immediate concern for management of dredged material. Major classes of contaminants of concern in dredged material management currently include metals such as mercury and cadmium; polycyclic aromatic hydrocarbons (PAHs), especially petroleum-derived PAHs; known or potentially carcinogenic compounds such as dioxin; and organochlorine compounds such as polychlorinated biphenyls (PCBs).

The scope of this study does not include air-breathing organisms (for example, marine mammals, sea turtles, reptiles, piscivorous birds, terrestrial biota). A more comprehensive review of the data presented herein is available in Suedel and others (1994).

Background

Potential ecological effects of sediment-associated contaminants are of concern, particularly in the context of dredged material management. Sediments can serve as contaminant sources for transport and exposure to aquatic biota, particularly when sediments are disturbed by physical perturbations such as storms, bioturbation, or dredging and aquatic placement of dredged material. Sediment-sorbed contaminants may accumulate sufficiently in the tissues of prey organisms to elicit direct adverse effects, and may be transferred to consumers through dietary intake or by increased concentrations in the water column. Aquatic

organisms that bioaccumulate contaminants from water or sediment may transfer these contaminants to predators that forage on them.

Of special interest is the extent to which these sediment-associated contaminants can move through aquatic food webs and thus potentially affect organisms at higher trophic levels. This trophic transfer potential must be known in order to determine the environmental significance of the bioaccumulation of sediment-associated materials in aquatic organisms.

Additional Information

For additional information, contact the authors, Dr. Thomas M. Dillon, U.S. Army Engineer Waterways Experiment Station, (601) 634-3922; Dr. Burton C. Suedel, Dr. Richard K. Peddicord, Dr. Philip A. Clifford, and Ms. Jane A. Boraczek, EA Engineering, Science, and Technology, Inc., (410) 584-7000; or the manager of the Environmental Effects of Dredging Programs, Dr. Robert M. Engler, (601) 634-3624.

Introduction

The terms bioconcentration, bioaccumulation, biomagnification, trophic transfer, and trophic transfer coefficient are defined below to avoid confusion, as they have been used inconsistently throughout the literature (Dallinger and others 1987).

Bioconcentration is the uptake of a contaminant by aquatic organisms where water is the sole contaminant source. Bioaccumulation is the uptake of a contaminant from both water and dietary sources. Biomagnification refers to the processes of both bioconcentration and bioaccumulation that result in increased tissue concentrations of a contaminant as it passes through two or more trophic levels (Macek, Petrocelli, and Sleight 1979).

Trophic transfer is defined as the transport of contaminants between two trophic levels (that is, prey to predator) (Swartz and Lee 1980). Trophic transfer coefficient (TTC) is the concentration of contaminant in consumer tissue divided by the concentration of contaminant in food sources (that is, preceding trophic level). A TTC is an approximate measure of the potential for a contaminant to biomagnify. Biomagnification occurs when concentrations of a material increase between two or more trophic levels (that is, TTC >1) and is a subset of trophic transfer, which refers to any movement of a material between trophic levels (that is, TTC can be greater than or less than 1). If trophic transfer is determined to be substantially >1, biomagnification is said to occur. If a TTC value is ≤1, biomagnification is judged not to take place.

Approach

This review was conducted in two phases. In Phase I, information from the published literature demonstrating contaminant trophic transfer (or lack thereof) in laboratory and field experiments was reviewed and summarized. Studies examining annelids and molluscs as potential first-level bioaccumulators of contaminants from sediments were emphasized since these organisms are used extensively to assess regulatory-mandated sediment bioaccumulation potential (U.S. Environmental Protection Agency/U.S. Army Corps of Engineers 1991). Whenever possible, results were expressed quantitatively as chemical-specific TTCs.

In Phase II, the TTCs and estimates of overall potential for contaminant trophic transfer through aquatic food webs from Phase I were compared with appropriate data from published aquatic food web models. Phase II was designed to determine the applicability of laboratory and modeling results in predicting contaminant-specific trophic transfer potential. General conclusions were then drawn concerning whether biomagnification (with regard to categories of contaminants and groups of organisms) occurs within aquatic systems and, if so, its relative frequency of occurrence, magnitude, and estimates of uncertainty.

Peer-reviewed literature was obtained from a variety of sources including electronic database and chain-of-citation searches. Approximately 300 articles published since 1969 were obtained and screened for relevant information. Over 100 manuscripts from the published literature were selected for detailed review based on the reporting of contaminant tissue data, allowing for the determination of contaminant TCC values.

Emphasis was placed on articles containing measured contaminant tissue concentrations of organisms comprising potential predator-prey relationships of aquatic food webs. As part of this review, results from laboratory experiments were compared with field results whenever possible.

Results and Discussion

Phase I, Literature Review—Metals

Most metals that were examined showed potential for trophic transfer uptake from food, but not in sufficient quantities to result in biomagnification (Figure 1). Those metals that showed a propensity to biomagnify include arsenic and methyl mercury, and perhaps mercury.

Arsenic was the only compound examined that showed a clear trend of increased TTC values with increased trophic level. This relationship was found only in marine food webs, as no supporting data for freshwater aquatic food webs was found. Cadmium also appears to biomagnify in aquatic food webs; however, all TTC values for cadmium calculated in this review as >2.4 were for marine gastropods. Some marine gastropod species apparently have the

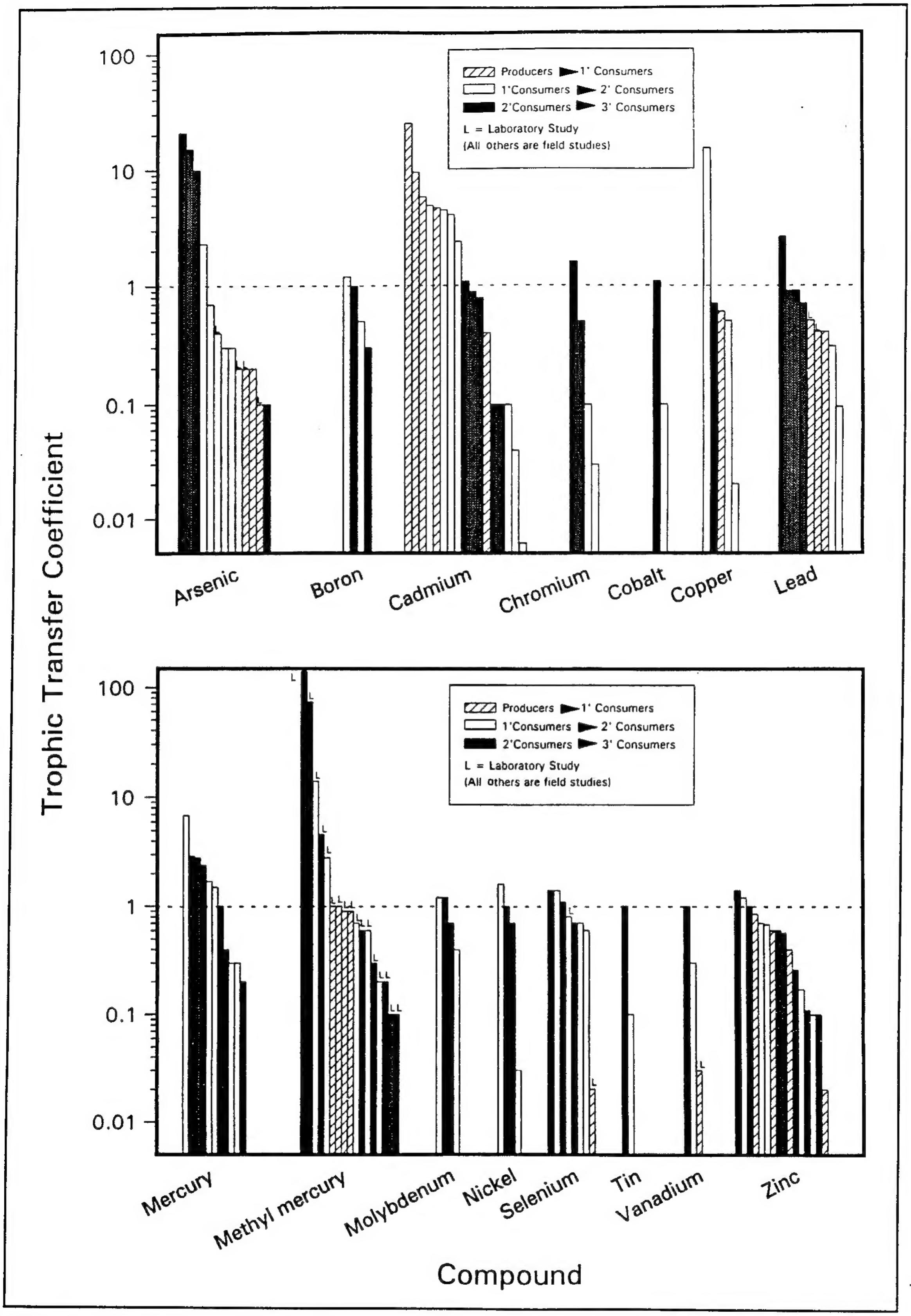

Figure 1. Trophic transfer coefficients for metals examined in this study. (TCC values >1 indicate a potential for biomagnification in aquatic ecosystems)

capacity to sequester cadmium in their tissues (the physiological significance for this is unknown).

Concentrations of most metals were often higher in tissues of producers and primary consumers than top-level carnivores (Klump and Peterson 1979; Ward, Connell, and Anderson 1986). Often, organisms feeding directly on sediments (such as crab and shrimp) and filter-feeders (such as bivalve molluscs) had the highest metal body burdens (LeBlanc and Jackson 1973; Hardisty and others 1974; Ward, Connell, and Anderson 1986; Kiorboe, Mohlenberg, and Riisgard 1983).

These results were consistent with the findings of Bryan (1979) and Dallinger and others (1987). Bryan (1979) noted that food web transfer was a significant source of metals to predator species such as fish. He noted that fish tissue levels were dependent primarily on the ability of the fish to excrete or store the contaminant. In addition to fish, decapods, polychaete worms, and bivalve molluscs were found to have the ability to regulate some essential metals such as zinc and copper, but not nonessential metals such as cadmium and lead (Bryan 1979, Bryan and Langston 1992, Lewis and Cave 1982). The fact that oysters, other bivalve molluscs, and aquatic organisms such as fish accumulate some metals for physiological requirements must be considered before concluding that biomagnification of these metals is occurring in aquatic food webs.

Phase I, Literature Review—Organics

From the data reviewed, PCBs, DDT, DDE, and toxaphene have the potential to biomagnify in aquatic ecosystems (Figure 2). Most of the accumulation of these contaminants was in secondary and tertiary consumer organisms. However, few if any data were found for lower tropic level organisms for toxaphene and DDT. Studies examining DDT and PCB accumulation observed higher tissue burdens in top carnivorous species such as salmonids and bass (Oliver and Niimi 1988, Niethammer and others 1984) and were attributed to the lipophilic nature of these compounds and exposure duration. Top carnivores often had the highest lipid content and longest life spans relative to organisms at lower trophic levels. Generally speaking, biomagnification data were lacking for producers and primary consumers for most organic compounds. Other organics reviewed do no appear to biomagnify in aquatic ecosystems.

Phase II, Trophic Transfer Models

Bioenergetic-based models (food web models) are used to predict contaminant concentrations in organism tissues at several levels through aquatic food webs (Thomann and Connolly 1984, Thomann 1989). One of the most rigorous studies predicting food web biomagnification (or the lack thereof) of organic compounds by a food chain model was conducted by Thomann (1989). Thomann's model was used in this review to compare model predictions to "real world" biomagnification potential. This was accomplished by comparing model predictions with calculated TTC values for organic compounds examined in this review. Only tissue residue data for small fish-predacious fish food

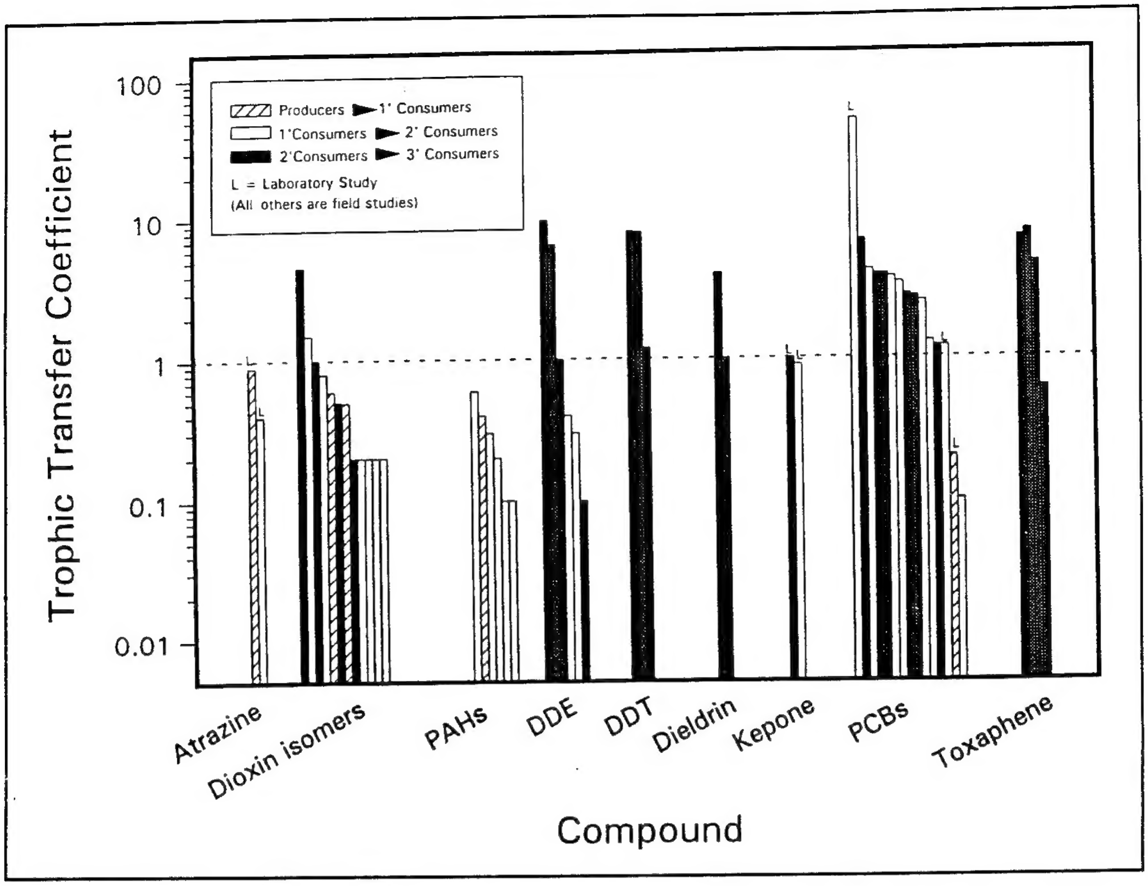

Figure 2. Trophic transfer coefficients for organic compounds examined in this study. (TCC values >1 indicate a potential for biomagnification in aquatic ecosystems)

chains obtained during this review and from the Thomann model were used for comparison. Trophic transfer coefficients for dioxin isomers (TCDD), PCBs (as Aroclor 1254), DDT, DDE, dieldrin, toxaphene, and kepone obtained from this review were plotted against values calculated from the model for these compounds (Figure 3).

As shown in Figure 3, the Thomann model generally provided numerically lower estimates of the potential for the organic compounds examined (log K_{ow} values between 5 and 6.5) to biomagnify in aquatic ecosystems. TTC values calculated by the model were 2 to 10 times lower than most median TTC values obtained for small fish-predacious fish food chains in this review.

For kepone, predictions of trophic transfer from the model and this literature review were virtually identical (TTC = 0.9). All TTC values for dieldrin and toxaphene from this review were higher than the TTC values predicted by the model, resulting in median values for these compounds considerably above model predictions. The model produced higher trophic transfer potential for Aroclor 1254 and 2,3,7,8-TCDD (log K_{ow} values between 6.5 and 7) than reported in this literature review.

Except for toxaphene and dieldrin, model predictions were within the range of TTC values found in this review.

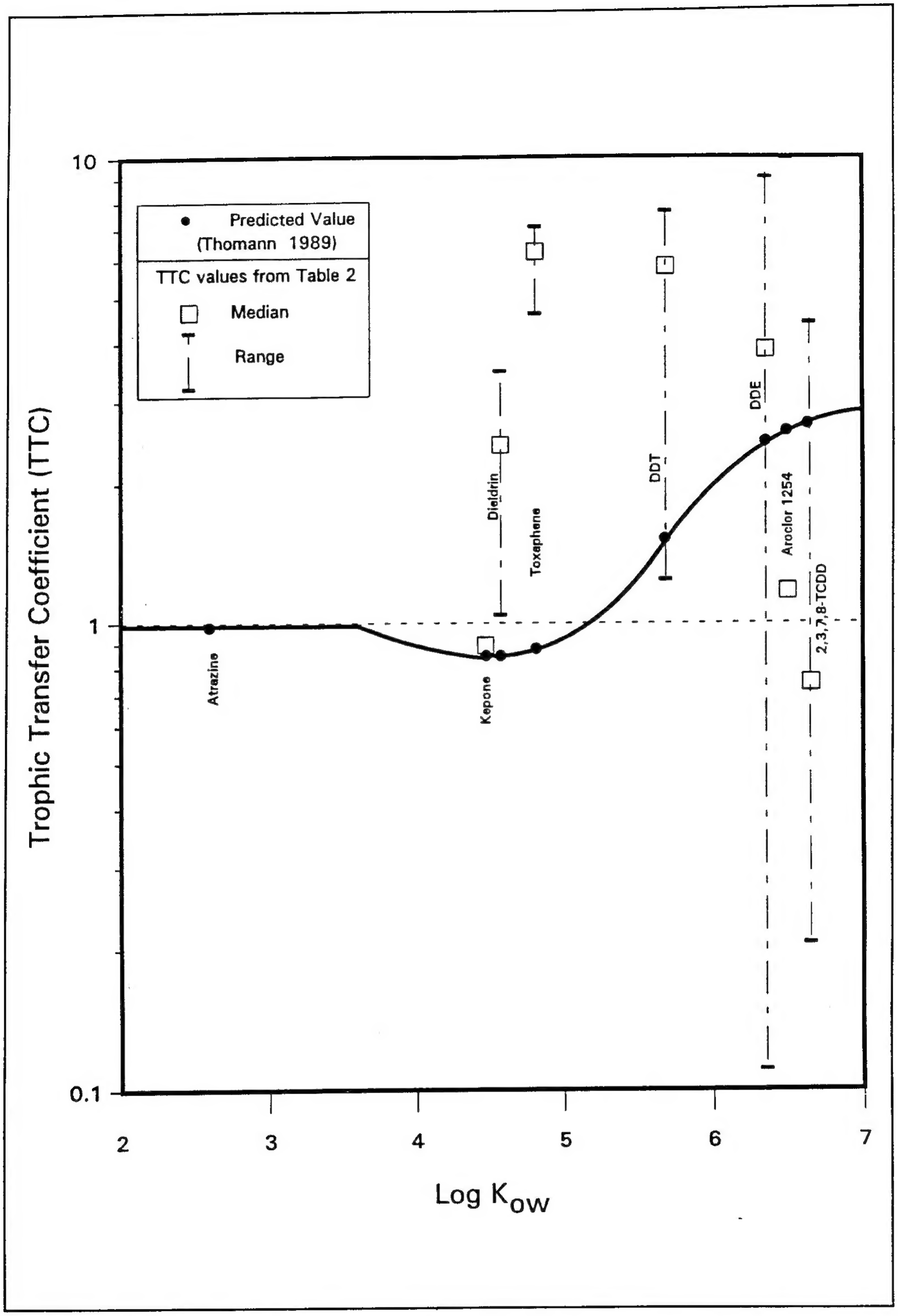

Figure 3. Plot of trophic transfer coefficients versus log K_{OW} values for selected organic compounds compared to values predicted by the food chain model by Thomann (1989)

Aquatic Food Web Biomagnification—Evidence

The data reviewed in this study are in general agreement with the results of other investigators examining the potential for aquatic food web biomagnification (Biddinger and Gloss 1984, Kay 1984). All three studies concluded that PCBs and methyl mercury have the potential to biomagnify in aquatic food webs (Table 1). As in this review, Biddinger and Gloss (1984) also concluded that total mercury and DDT have the potential to biomagnify. The results from this review and Biddinger and Gloss (1984) generally agree that only highly water-insoluble organic compounds have the potential to biomagnify in aquatic food webs (that is, DDT, PCBs). Results from Thomann's model also indicated that highly water-insoluble compounds (log k_{ow} values 5 to 7) showed the greatest potential to biomagnify. However, the model also included other organic compounds that were not observed to biomagnify in this study, such as TCDD (log K_{ow} = 6.6).

As was also observed in an earlier review by Kay (1984), studies examining contaminant biomagnification were often plagued by methodological problems. The variability observed in results for individual compounds may be attributed to many factors, including uncertainty regarding an organism's position in a food web, contrived laboratory food chains that do not effectively represent actual feeding relationships in the field, unknown feeding habits of organisms examined, inadequate sampling (that is, one sample at a given time and location), sampling at different times and locations, and lack of standardization of units of measurement (fresh weight, dry weight, lipid normalized).

Results reported for tissue levels based on wet weights or lipid normalized data can influence the TTC considerably, since percent water and percent lipid have been demonstrated to vary considerably with age, body weight, season, and physiological condition of the organism (Kay 1984). Often, the organisms examined within a particular study did not fit in a logical food chain, with several organisms potentially occupying a given trophic level. Many studies made no effort to identify predator-prey relationships between organisms and trophic levels, making it difficult to determine whether contaminant trophic transfer could actually occur.

In other studies, tropic levels were well defined but other factors that may affect conclusions regarding biomagnification potential were not considered. For example, if gut contents of predators were not analyzed, definitive statements regarding their food source(s) or proportions cannot be made. Individual age and size can influence body burdens, particularly for younger, smaller organisms with high potential for growth dilution (Bryan 1979). Methodological problems such as those listed above severely limit the conclusions that can be made regarding trophic transfer and biomagnification of most contaminants in aquatic ecosystems.

Few, if any, data exist on the potential for numerous organic compounds and metals to biomagnify in aquatic systems, especially those compounds that are not hypothesized to readily biomagnify. Thus, conclusions regarding their

Table 1. Compounds for Which Available Information Exists for Potential Food Chain Biomagnification to Occur in Aquatic Ecosystems

Compound	Source: Biddinger and Gloss (1984)	Source: Kay (1984)	Source: This Study
Most Evidence for Potential Biomagnification			
Methyl mercury	Yes	Yes	Yes
PCBs	Yes	Yes	Yes
Some Evidence for Potential Biomagnification			
Arsenic	No	No	Yes
Mecury (total)	Yes	No	Yes
Selenium	Yes	No	No
Zinc	Yes	No	No
Benzo[a]pryrene	No	Yes	No
DDT	Yes	No	Yes
DDE	—[1]	No	Yes
Dieldrin	—	Yes	No
Endrin	No	Yes	—
Kepone	—	Yes	No
Mirex	—	Yes	No
Toxaphene	—	—	Yes
No Evidence for Potential Biomagnification			
Beryllium	No	—	—
Boron	—	—	No
Cadmium	No	No	No
Chromium	No	No	No
Cobalt	—	—	No
Copper	No	No	No
Lead	No	No	No
Molybdenum	—	—	No
Nickel	No	No	No
Silver	No	No	—
Tin	—	No	No
Vanadium	—	—	No
Aldrin/dieldrin	No	No	—
Atrazine	—	No	No
Chlordane	No	—	—
Chlorinated benzenes	No	No	—
Chlorinated phenols	No	No	—
Endosulfan	No	No	—
Heptachlor	No	—	—
HCH	No	—	No
Lindane	—	No	—
PAH	No	No	No
Phthalate esters	No	—	—
TCDD	No	—	No

[1] Not examined.

potential to biomagnify cannot be made until data are available. From the data reviewed in this study and others, when the potential for food web biomagnification was evident in aquatic food webs, TTC values were generally between 1 and 10, rather than hundreds or thousands, as reported for non-aquatic food webs (Kay 1984).

Conclusions

Food web biomagnification of contaminants in freshwater and marine ecosystems is not well substantiated in the literature. Results of this review suggest that most metal and organic contaminants appear to have a low potential for trophic transfer and are therefore not likely to biomagnify in aquatic food webs. Data reviewed in this study indicate that DDT, DDE, PCBs, toxaphene, total and methyl mercury, and arsenic have the potential to biomagnify (Table 1; Figures 1-2). For most compounds examined, data were variable, with TTC values varying 2 to 3 orders of magnitude for arsenic, zinc, methyl mercury, and cadmium.

Evidence from this review suggests that most biologically available contaminants associated with sediment or dredged material may undergo trophic transfer but would not biomagnify in aquatic food webs. From the combined evidence of this and other reviews (Biddinger and Gloss 1984, Kay 1984), if sediment-associated PCBs and methyl mercury were to bioaccumulate in organisms such as bivalve molluscs and polychaetes, these two contaminants will likely have a greater potential to biomagnify in aquatic ecosystems than other contaminants (Table 1). If biomagnification of these contaminants takes place in aquatic food webs, the TTC values from bottom to top of the food webs are likely to be on the order of 1 to 10, rather than hundreds to thousands as observed for some nonaquatic food webs (Kay 1984).

Additional, carefully designed, scientifically defensible and repeatable research is needed to clarify whether these and numerous other compounds have the potential to biomagnify in aquatic food webs. Until then, predictions of whether aquatic organisms will experience biomagnification when exposed to these compounds will remain uncertain.

References

Biddinger, G. R., and Gloss, S. P. 1984. "The Importance of Trophic Transfer in the Bioaccumulation of Chemical Contaminants in Aquatic Ecosystems," *Residue Reviews*, Vol 91, pp 103-145.

Bryan, G. W. 1979. "Bioaccumulation of Marine Pollutants," *Philosophical Transactions, Royal Society of London, Series B, Biological Sciences*, Vol 286, pp 483-505.

Bryan, G. W., and Langston, W. J. 1992. "Bioavailability, Accumulation and Effects of Heavy Metals in Sediments with Special Reference to United Kingdom Estuaries: A Review," *Environmental Pollution*, Vol 76, pp 89-131.

Dallinger, R., Prosi, F., Segner, H., and Back, H. 1987. "Contaminated Food and Uptake of Heavy Metals by Fish: A Review and a Proposal for Further Research," *Oecologia*, Vol 73, pp 91-98.

Hardisty, M. W., Huggins, R. J., Kartar, S., and Sainsbury, M. 1974. "Ecological Implications of Heavy Metal in Fish from the Severn Estuary," *Marine Pollution Bulletin*, Vol 5, pp 12-15.

Kay, S. H. 1984. "Potential for Biomagnification of Contaminants Within Marine and Freshwater Food Webs," Technical Report D-84-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kiorboe, T., Mohlenberg, F., and Riisgard, H. U. 1983. "Mercury Levels in Fish, Invertebrates, and Sediment in a Recently Recorded Polluted Area (Nissum Broad, Western Limfjord, Denmark), *Marine Pollution Bulletin*, Vol 14, pp 21-24.

Klump, D. W., and Peterson, P. J. 1979. "Arsenic and Other Trace Elements in the Waters and Organisms of an Estuary in Southwestern England," *Environmental Pollution*, Vol 19, pp 11-20.

LeBlanc, P. J., and Jackson, A. L. 1973. "Arsenic in Marine Fish and Invertebrates," *Marine Pollution Bulletin*, Vol 4, pp 88-90.

Lewis, A. G., and Cave, W. R., 1982. "The Biological Importance of Copper in Oceans and Estuaries," *Oceanography and Marine Biology: An Annual Review*, Vol 20, pp 471-695.

Macek, K. J., Petrocelli, S. R., and Sleight, B. H., III. 1979. "Consideration in Assessing the Potential for, and Significance of, Biomagnification of Chemical Residues in Aquatic Food Chains," *Aquatic Toxicology*, ASTM STP 667, L. L. Marking and R. A. Kimerle, eds., American Society for Testing and Materials, pp 251-268.

Niethammer, K. R., White, D. H., Baskett, T. S., and Sayre, M. W. 1984. "Presence and Biomagnification of Organochlorine Chemical Residues in Oxbow Lakes of Northeastern Louisiana," *Archives of Environmental Contamination and Toxicology*, Vol 13, pp 63-74.

Oliver, B. G., and Niimi, A. J. 1988. "Trophodynamic Analysis of Polychlorinated Biphenyl Congeners and Other Chlorinated Hydrocarbons in the Lake Ontario Ecosystem," *Environmental Science and Technology*, Vol 22, pp 388-397.

Suedel, B. C., Boraczek, J. A., Peddicord, R. K., Clifford, P. A., and Dillon, T. M. 1994. "Trophic Transfer and Biomagnification Potential of Contaminants in Aquatic Ecosystems," *Reviews of Environmental Contamination and Toxicology*, Vol 136, pp 21-89.

Swartz, R. C., and Lee, H. 1980. "Biological Processes Affecting the Distribution of Pollutants in Marine Sediments; Part I, Accumulation, Trophic Transfer, Biodegradation and Migration," *Contaminants and Sediments; Vol 2, Analysis, Chemistry, Biology*, R. A. Baker, ed., Ann Arbor Science, Ann Arbor, MI.

Thomann, R. V., and Connolly, J. P. 1984. "Model of PCB in the Lake Michigan Lake Trout Food Chain," *Environmental Science and Technology*, Vol 18, pp 65-71.

Thomann, R. V. 1989. "Bioaccumulation Model of Organic Chemical Distribution in Aquatic Food Chains," *Environmental Science and Technology*, Vol 23, pp 699-707.

U.S. Environmental Protection Agency/U.S. Army Corps of Engineers. 1991. "Evaluation of Dredged Material Proposed for Ocean Disposal (Testing Manual)," EPA-503/8-91-001, USEPA, Washington, DC.

Ward, T. J., Connell, R. L., and Anderson, R. B. 1986. "Distribution of Cadmium, Lead and Zinc Amongst the Marine Sediments, Seagrasses and Fauna, and the Selection of Sentinel Accumulators, Near a Lead Smelter in South Australia," *Australian Journal of Marine and Freshwater Research*, Vol 57, pp 567-585.